Meeting The Needs of the Aerospace Industry: Accurate Simulation of Fabric Permeability

Advanced Composites Institute

Home of the **Marvin B. Dow Stitched Composites Development Center**
Mississippi Advanced Composites (MAC) Training Center

Wayne Huberty, PhD
Associate Director, Advanced Composites Institute

***FAA Technical Monitor**: Dave Stanley / **FAA Sponsors**: Cindy Ashforth, Larry Ilcewicz*


watch?
v=KVQM4vx64EY

How repeatable do you think these infusions would be?

What if we simulated the flow front? Would the simulation match these videos?
What if these parts were larger?
What if the part geometries were more complicated?

The market identified simulation as a problem.

- Use of simulation for resin infusion process design is uncommon
  - Trial and Error
  - Operator experience
- Ultimate goals of infusion simulation
  - Reduce waste and cost
  - Reduce necessary operator knowledge

How does one model an infusion process with commercially available software?

1. Resin flow
2. Thermal exchange between part and mold
3. Chemical reaction of resin

esi get it right

- Draping and Thermoforming
- Resin Transfer Molding (RTM), High-Pressure RTM and Compression RTM
- Resin Infusion and its variants
- Sheet Molding Compound (SMC)
- Curing and Crystallization
- Geometrical Distortions induced by the manufacturing process

Modeling an RTM process:

Flow

Darcy's Law

$$\vec{V} = -\frac{K}{\mu}\overrightarrow{\nabla P}$$

$\vec{V}$ = Darcy's velocity
K = permeability tensor
μ = viscosity of resin
P = pressure

"simplistic"

Unified Darcy's Equation

$$div\left(\frac{[K]}{\mu}\langle\nabla P\rangle\right) = \frac{d\varepsilon}{dt}$$

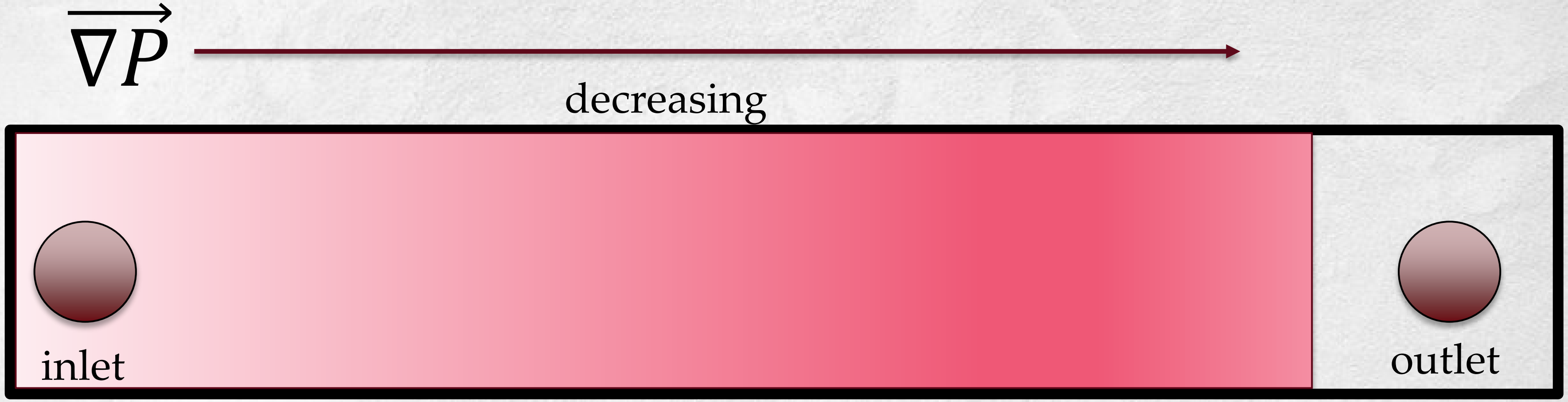
ε is deformation of the fiber bed

General form of mass conservation for deformable media (i.e. fabric).

"more advanced"

Modeling an RTM process:
Compaction forces

- Vacuum bagging (VARTM)



Rapid pressure drop can cause voids

- Vacuum (LP-RTM)
- Press (RTM, HP-RTM)

Key Factors Affecting Permeability:

FVF and nesting

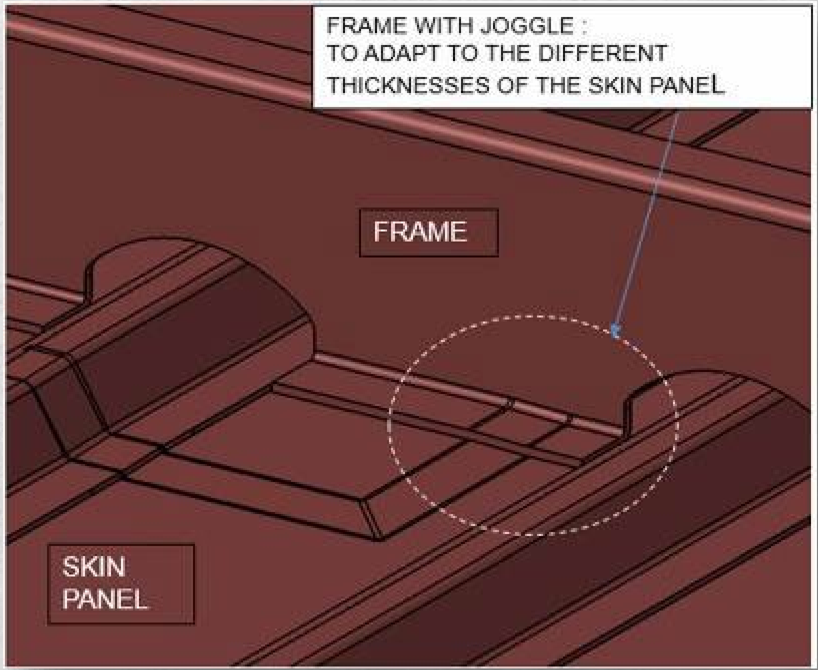
Various infusion processes may have different FVF and gradients thereof

Table 7 Measured fiber volume fractions for each manuf. method.[75]

Process	Fiber Volume Percentage
VARTM	-
FVF Inlet	47%
FVF Outlet	49%
SCRIMP	-
FVF Inlet	47.7%
FVF Outlet	47.9%
DBVI	-
FVF Inlet	45.4%
FVF Outlet	47.5%
VAP	-
FVF Inlet	50.2%
FVF Outlet	50.5%
CAPRI	-
FVF Inlet	51.8%
FVF Outlet	52.2%
PI	-
FVF Inlet	39.5%
FVF Outlet	48.7%

An objective comparison of common vacuum assisted resin infusion processes. *Compos. Part A Appl. Sci. Manuf.* **125**, 105528 (2019).

Complex shapes may perform differently for various infusion processes



32 layers pad up; 24 layers skin; Ω stiffener 16 layers

Design and manufacture of a reinforced fuselage structure through automatic laying-up and in-situ consolidation with co-consolidation of skin and stringers using thermoplastic composite materials, Heliyon, Volume 9, Issue 1, 2023,

Key Factors Affecting Permeability:
Laminate Thickness

Laminate Thickness

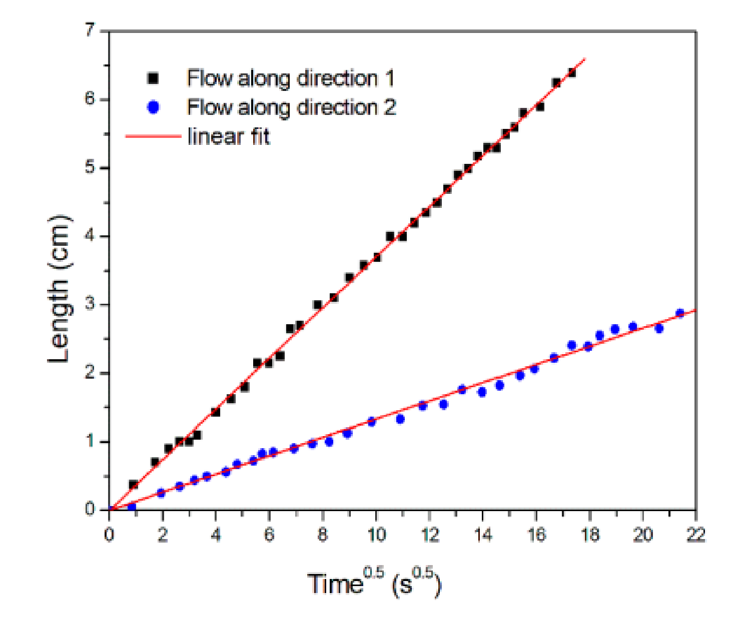
- Introduces complexity when in-plane flow is considered
  - Alternate flow pathways into low-permeability layers
- Accurate modeling of laminates required for simulation
  - Laminates with flow media, release fabric, etc.

Key Factors Affecting Permeability:
The fabric itself

Anisotropy

- UD fibers – High anisotropy
  - NCF, tape, etc.
  - Can cause bubbles
- Woven – Lower anisotropy

UD fibers



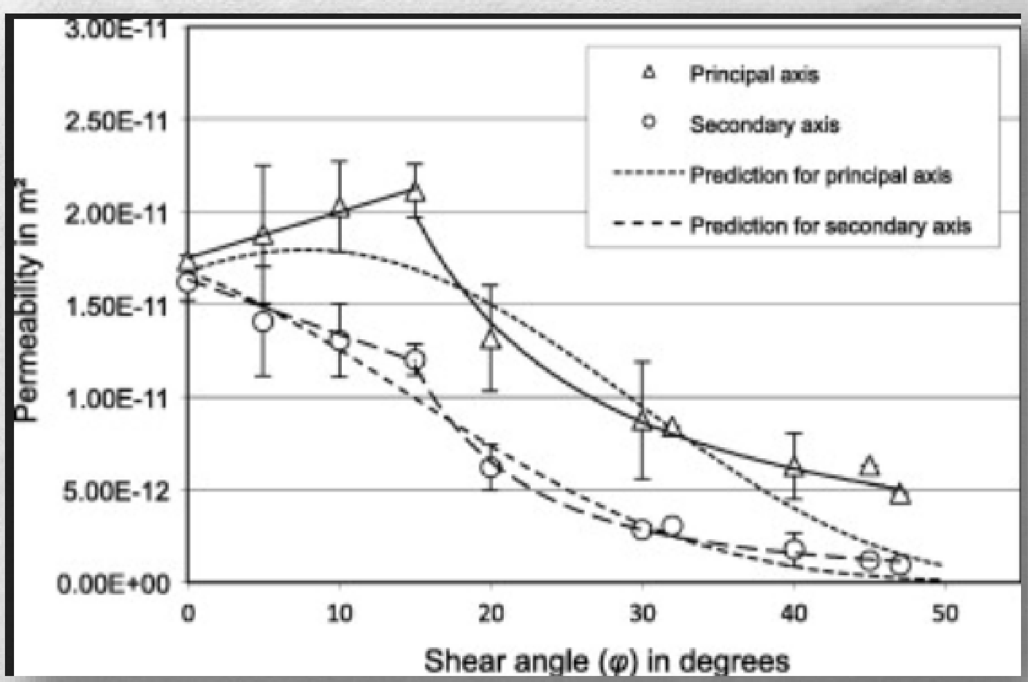
Materials 2020,13, 4800

Direction	Permeability
K1 (um^2)	2.81
K2 (um^2)	0.38
K3 (um^2)	0.043

Key Factors Affecting Permeability:
Fabric Shear

Fabric Shear

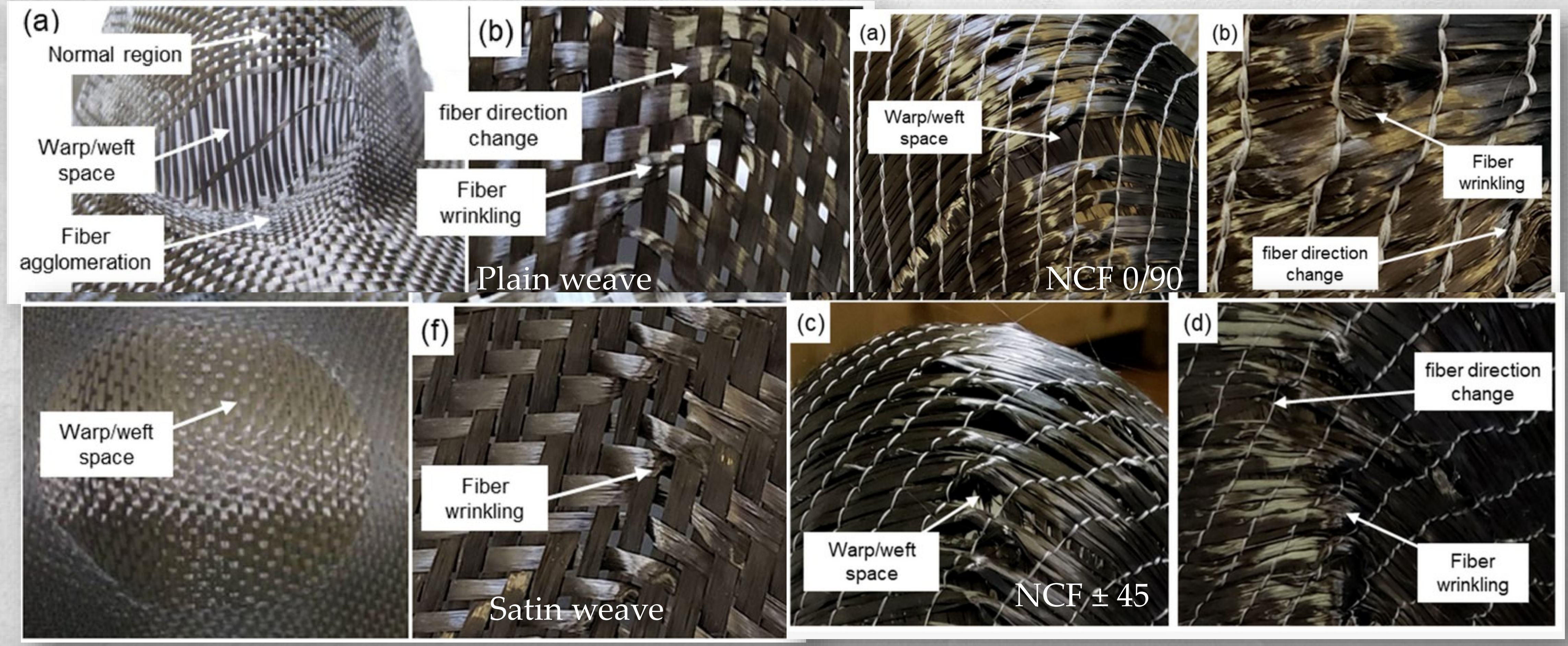
- Fiber tows are not perpendicular
- can be sheared over the entirety of the ply, or locally around changes in geometry
- Permeability change
  - Volume fraction changes with shear angle
  - Fiber tow reorientation can align flow directional components



Composites Part B: Engineering, Volume 65, 2014, Pages 158-163,

Key Factors Affecting Permeability:

Fabric Shear



Textiles **2022**, 2(3), 486-498; https://doi.org/10.3390/textiles2030027

Key Factors Affecting Permeability:

Capillary Forces

Capillary Action

- **Controversial**
- Senoguz – Surface tension measurements[1]
  - Capillary pressure too small compared to inlet pressure and can be ignored
- Amico and Lekakou – Experimental studies[2]
  - Capillary forces cannot be ignored at low infusion pressures (i.e. VARTM)
    - Can be as high as 5.4 PSI[3]

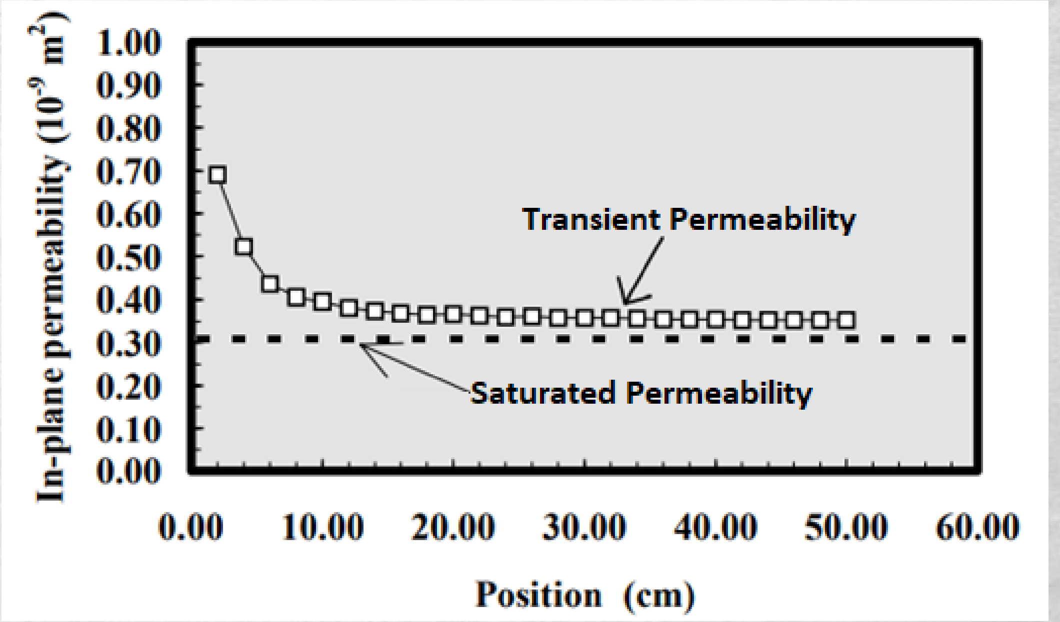
1. Journal of Composite Materials, vol. 35, no. 14/2001
2. Composites Science and Technology, vol.61(13), pp.1945-1959
3. Polymer Composites, June 1997, vol. 12, no. 3

Key Factors Affecting Permeability:

Transient vs Saturated Flow

Saturated vs. Transient Flow

- Saturated flow – steady-state, occurs once the fabric has been fully wetted by the permeating fluid
- Transient flow – occurs between wet and dry regions of the fabric



Proceedings of ICCM–11, Gold Coast, Australia, 14th-18th July 1997

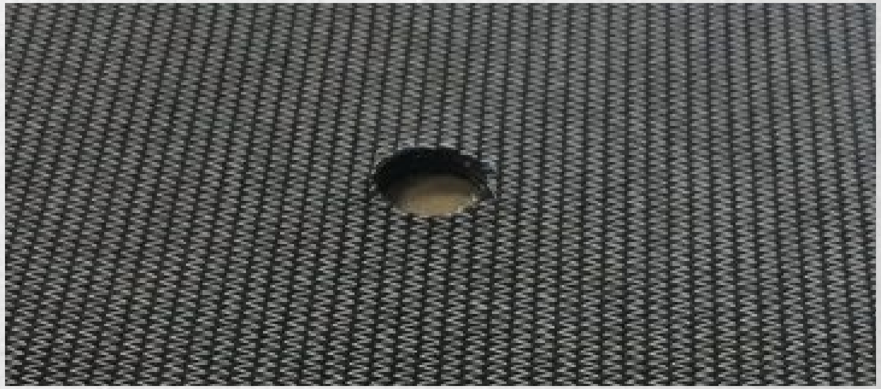
Methodology for Permeability Measurement

- Various methods for measuring permeability
  - 1-dimensional flow tests
    - Simple calculation and experimental design, saturated/unsaturated measurement
    - Race tracking along fabric edges, multiple tests needed for full characterization
  - Radial injection
    - No race tracking effects, simultaneous warp/weft measurements
    - More difficult setup, only unsaturated measurement
- Flow front tracking
    - Optical – Well-defined procedures, cheap equipment
    - Capacitive sensors – Test apparatus does not need to be optically clear, more expensive

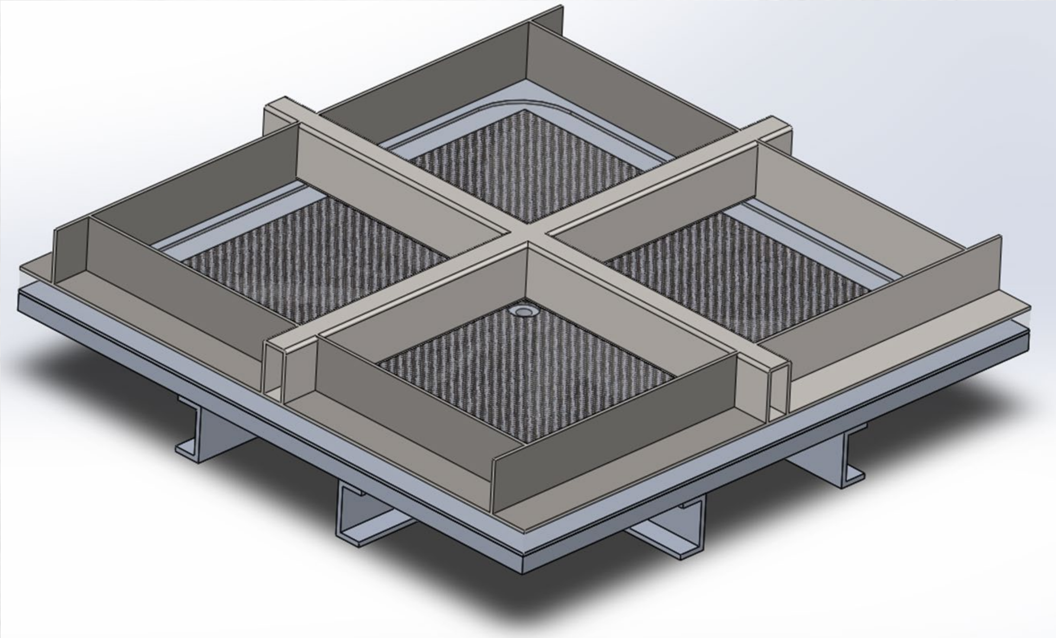
Permeability Measurement – Test Setup

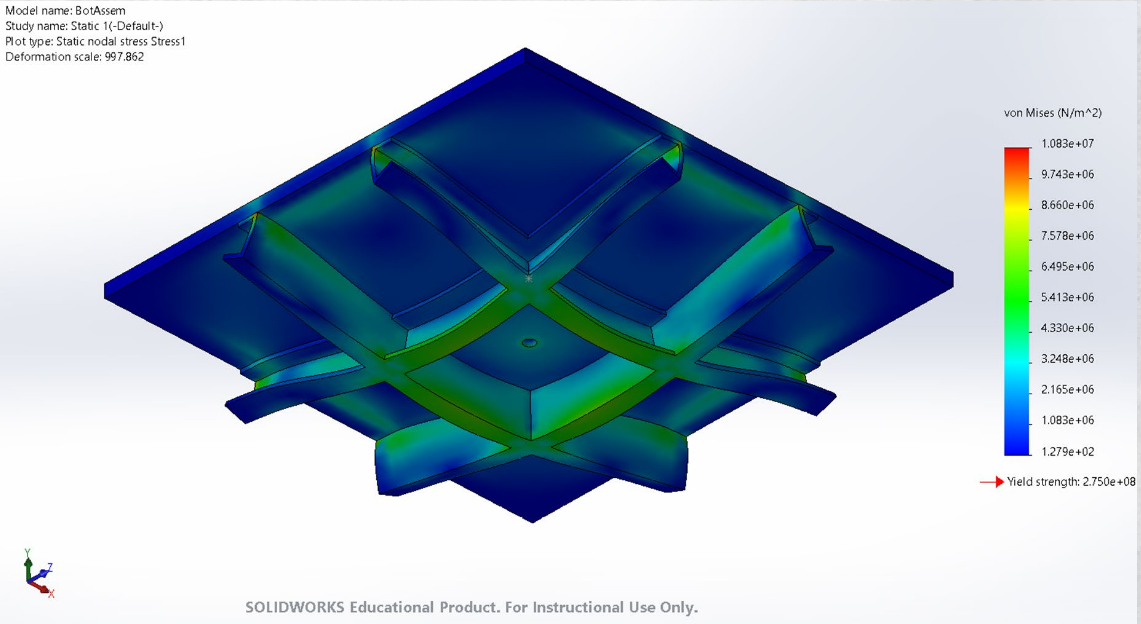
In-Plane Test

- Biaxial non-crimp fabric is cut to 10″ squares on CNC ply cutter table
- 1/4″ diameter hole punched in the center of each ply

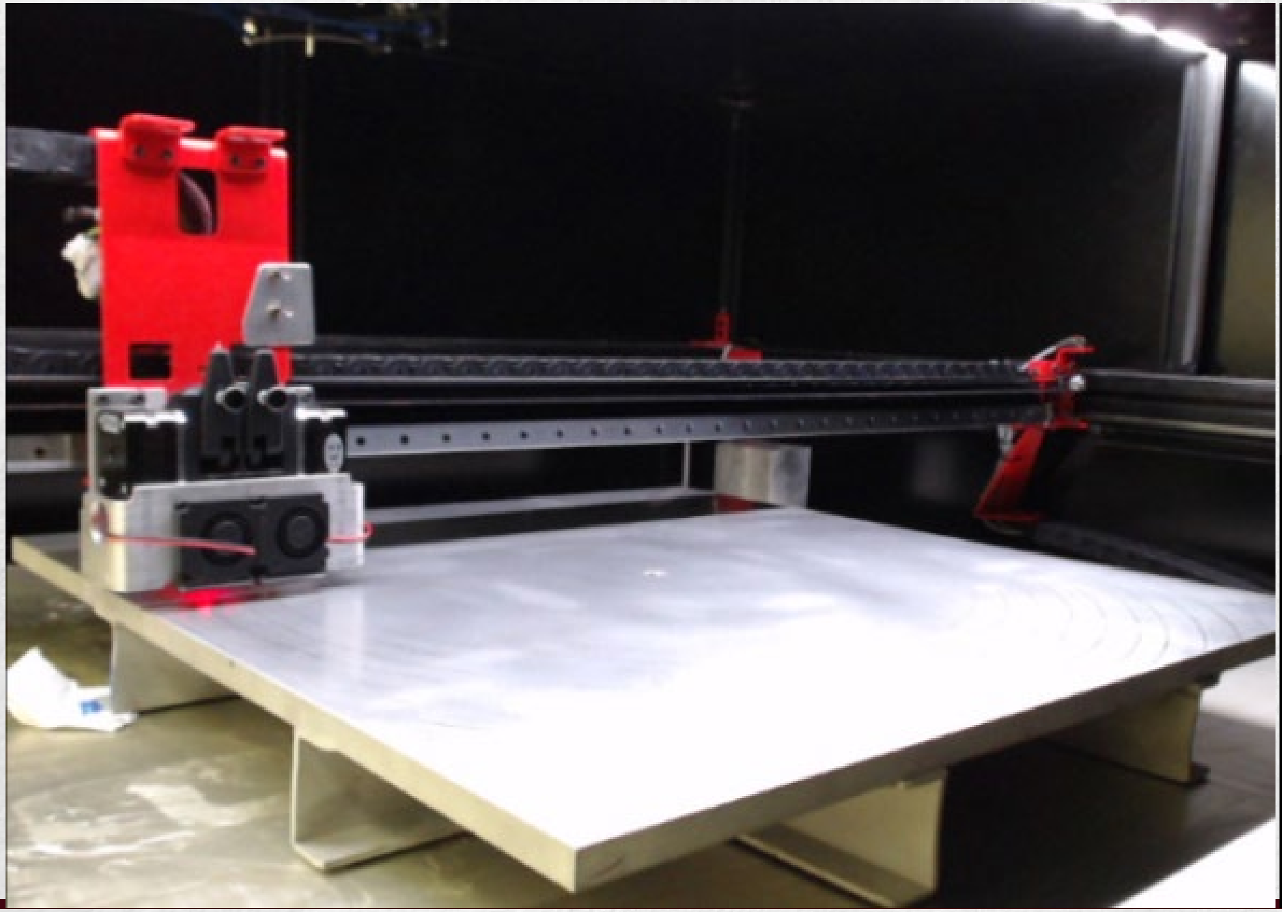


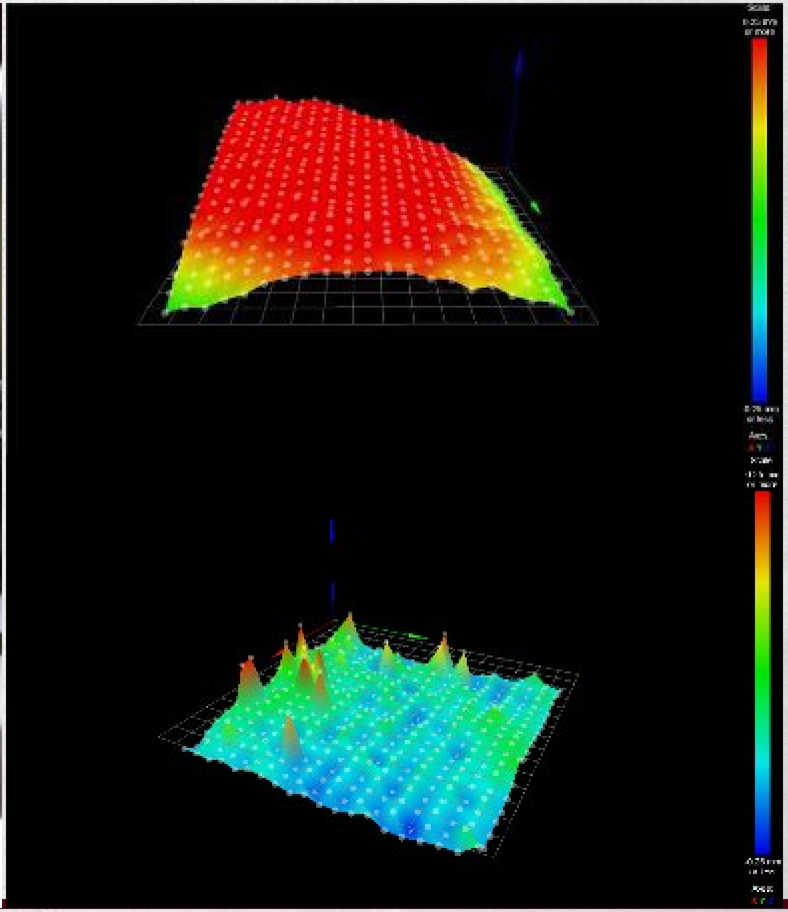
Permeability Measurement
Test Apparatus Design V1



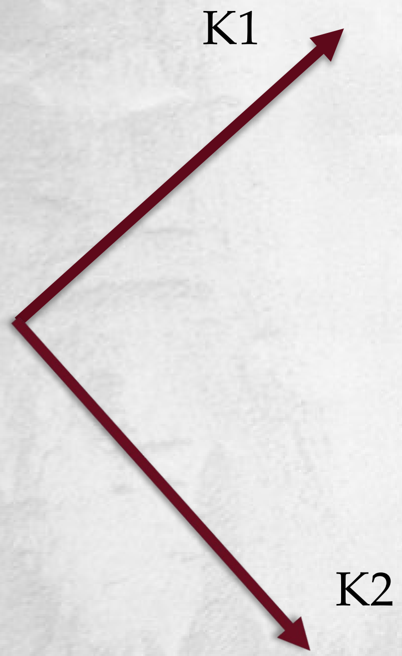


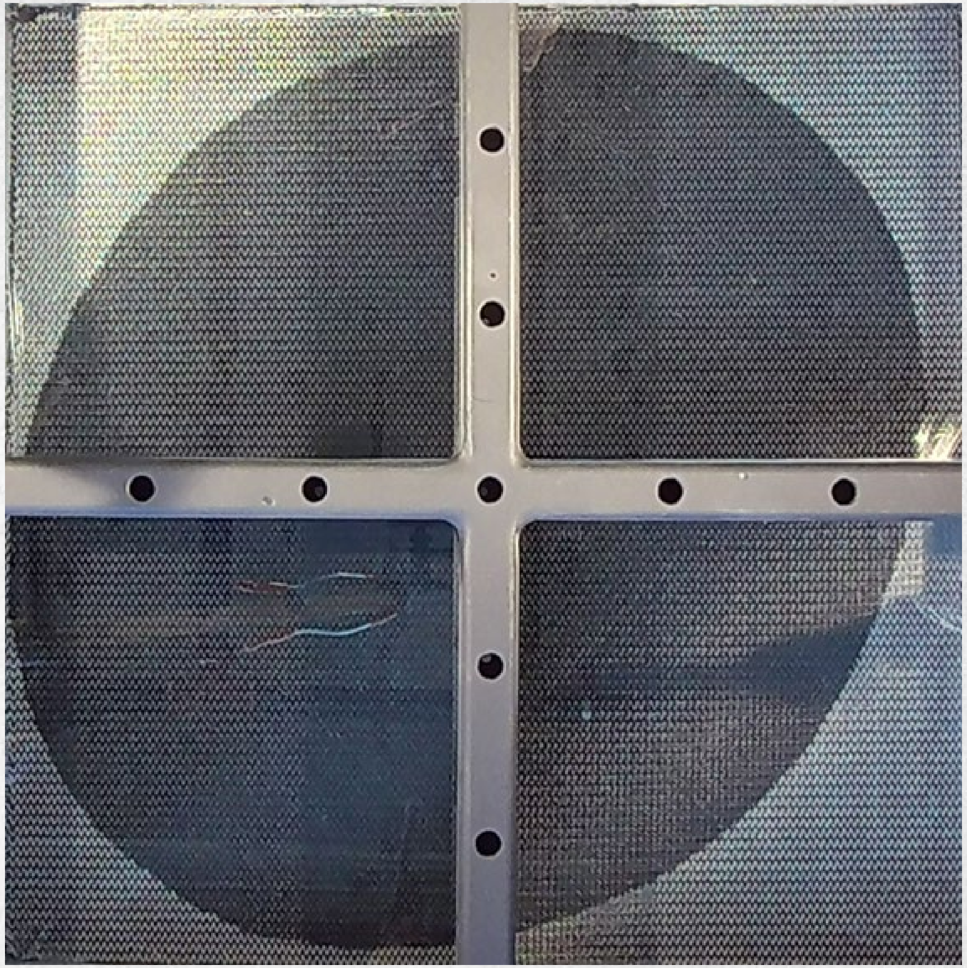
Bed leveling to measure flatness





Permeability Measurement – Test Results





PAM-RTM Simulation

Permeability Values at 52% FVF

	Fiber Permeability (m^2)	EasyPerm Fiber Permeability (m^2)	Flow Media Permeability (m^2)	Release Ply Permeability (m^2)
In-Plane (Warp)	2.76E-11	1.3E-11	2.50E-10	2.50E-12
In-Plane (Weft)	3.42E-11	1.2E-11	2.50E-10	2.50E-12
Through-Thickness	1.85E-12	1.8E-12	1.00E-09	2.00E-11

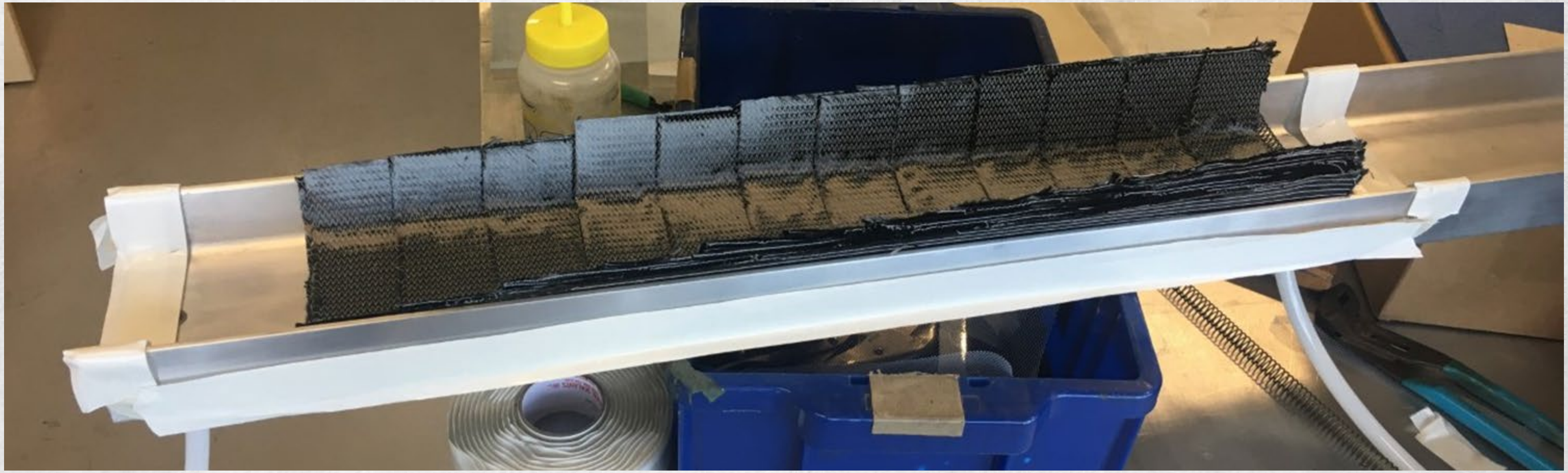
Measured values (Fiber, EasyPerm Fiber)

Assumed values (Flow Media, Release Ply)

Assumed values are unfavorable, but realistic.

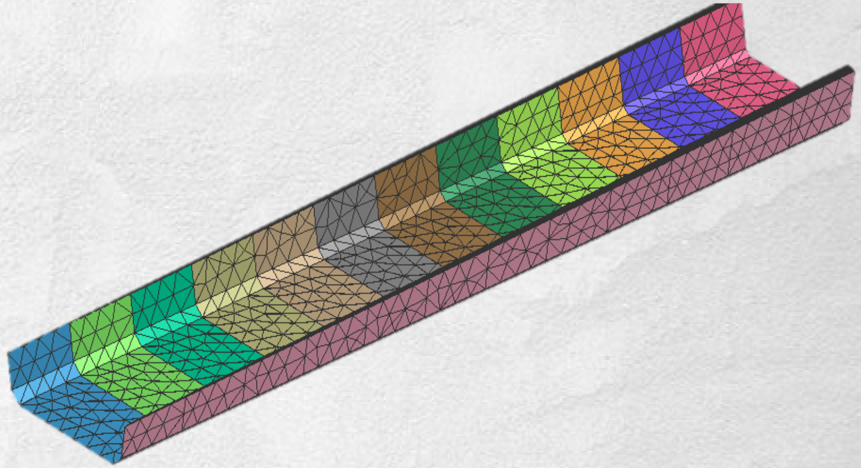
PAM-RTM Simulation – Comparison Case

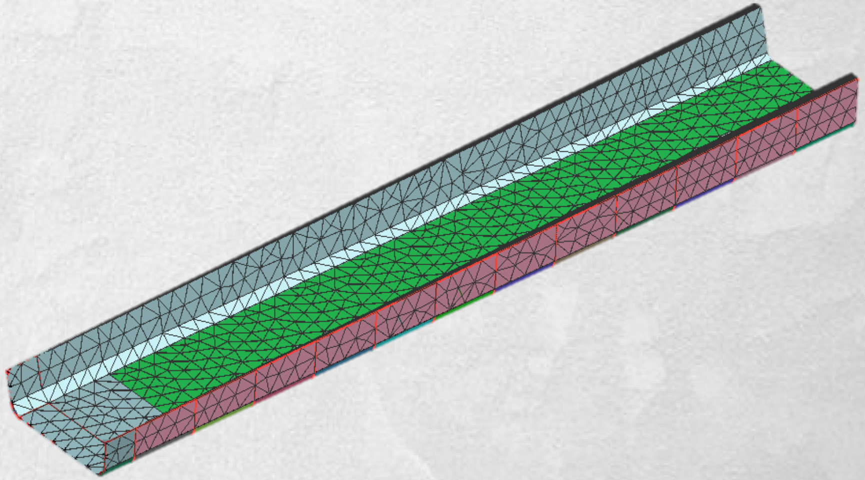
- A test case infusion was set up for comparison to the simulation result
- Infusion performed with 14.5psi vacuum at outlet, with 3psi vacuum at inlet



PAM-RTM Simulation – Setup

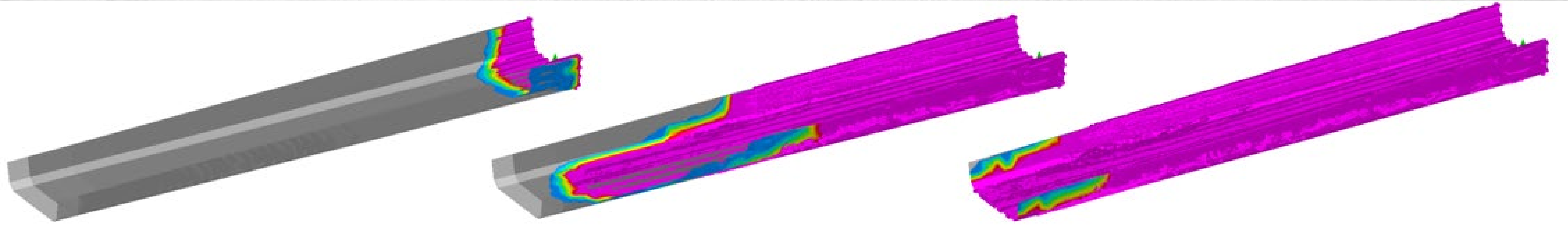
- A modified C-Channel
  - Tapered thickness (16→5 plies)
  - Tapered depth
- 3D tetrahedral elements
- Flow media and a Teflon release ply on top of the laminate





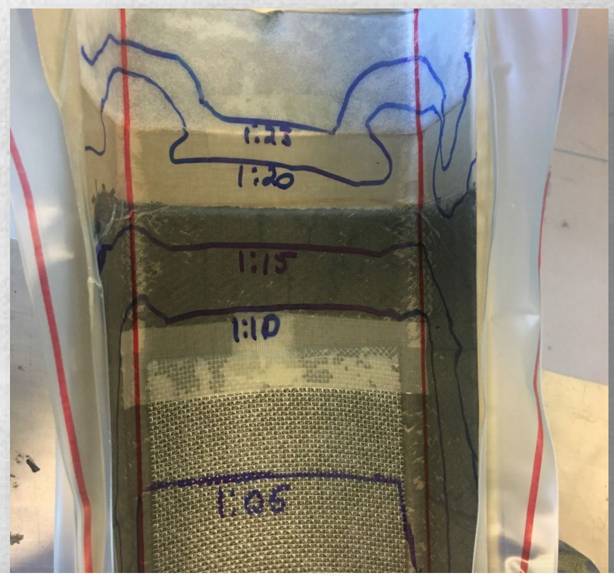
PAM-RTM Simulation – Results

- The simulation ran for ~3 hours and proceeded through 3,394 calculation steps
- Simulated filling time: 28.9 min
- Flow media was fully filled: 20.7 min
- Resin reached the end of the fiber preform: 22.1 min



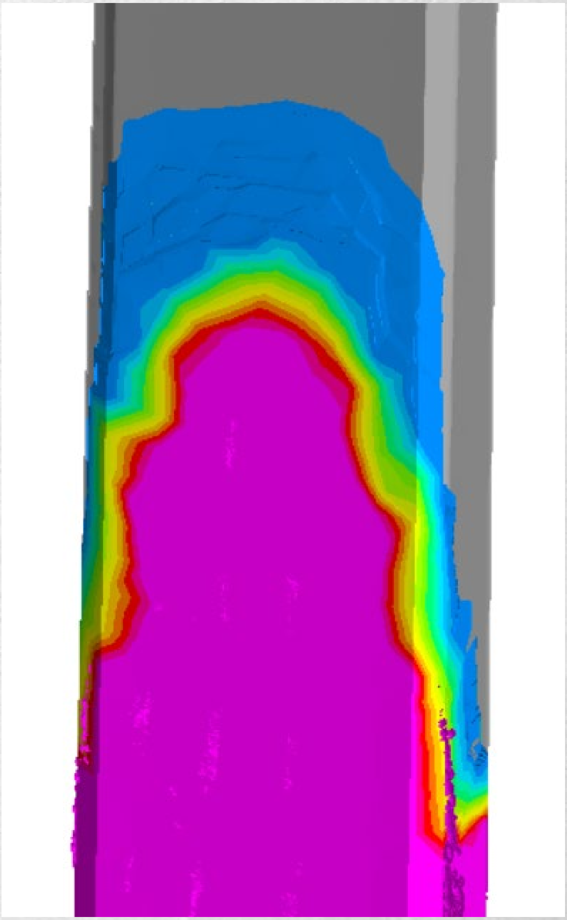
PAM-RTM Simulation – Comparison Case

- The test case stopped after 23 minutes
  - Complete filling of the carbon preform
  - Only small wet spots on 'resin brake' release ply area
  - Simulation: 28.9 min
- Flow media filled: 5-10 min
  - Simulation: 20.7 min
- Resin spread up the sides of the channel after flow media is filled, higher at end with inlet



PAM-RTM Simulation – Results

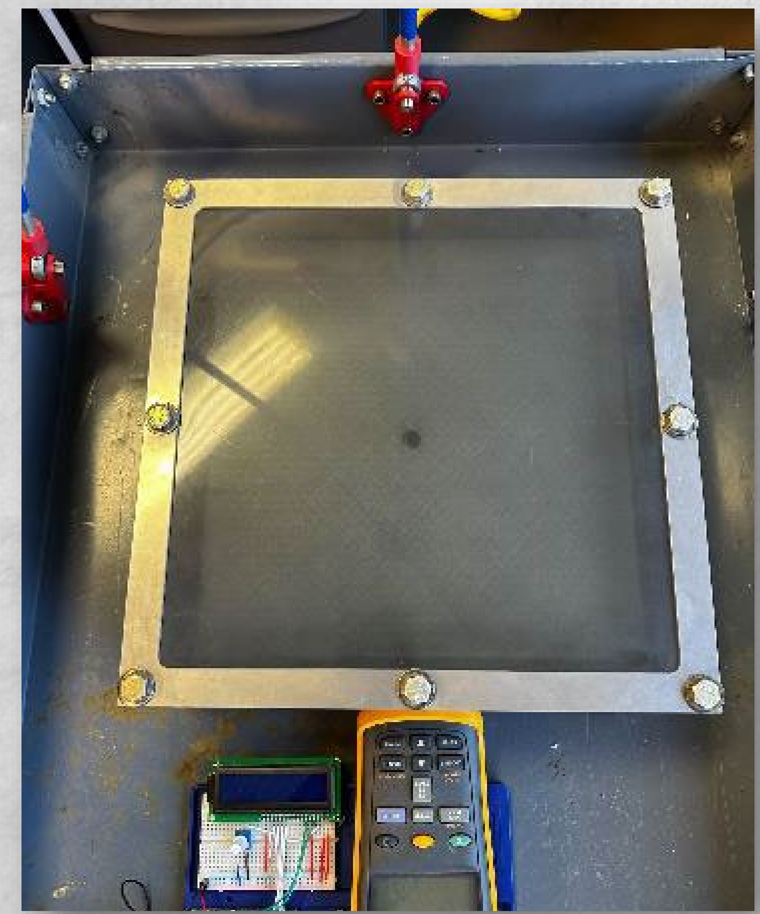
- Using 3D elements allows flow front visualization that isn't normally seen
- Total filling time – 25.7% error
- Simulation did not predict the flow front interaction between areas with and without flow media
- It is likely that the assumptions made about non-carbon laminate material permeability significantly affected the result

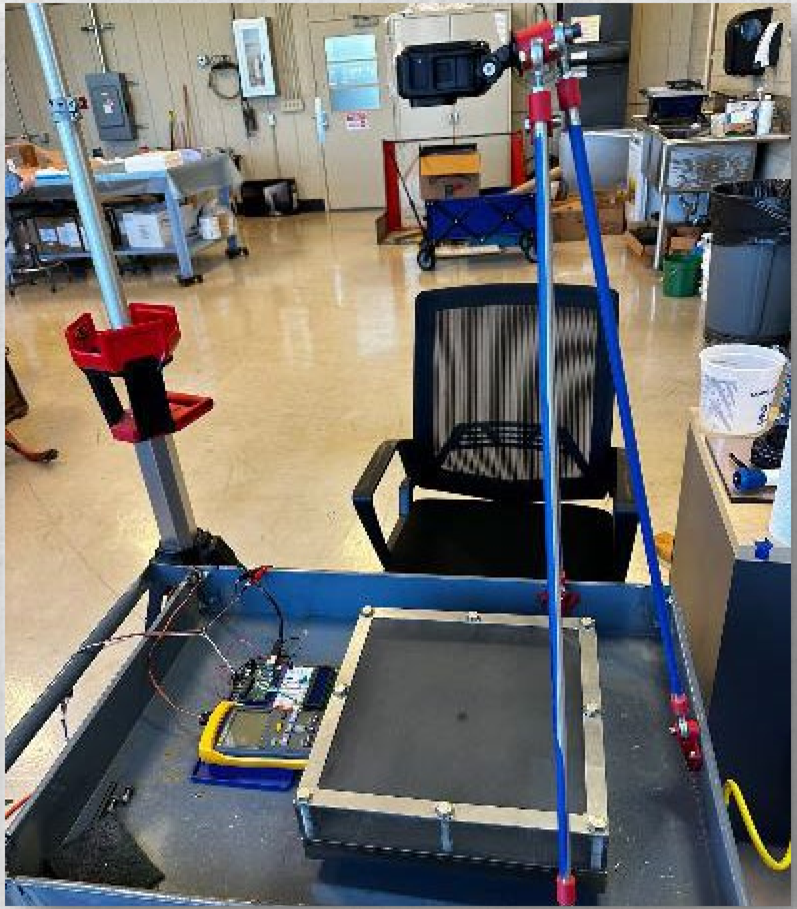


Permeability Measurement: Requirements

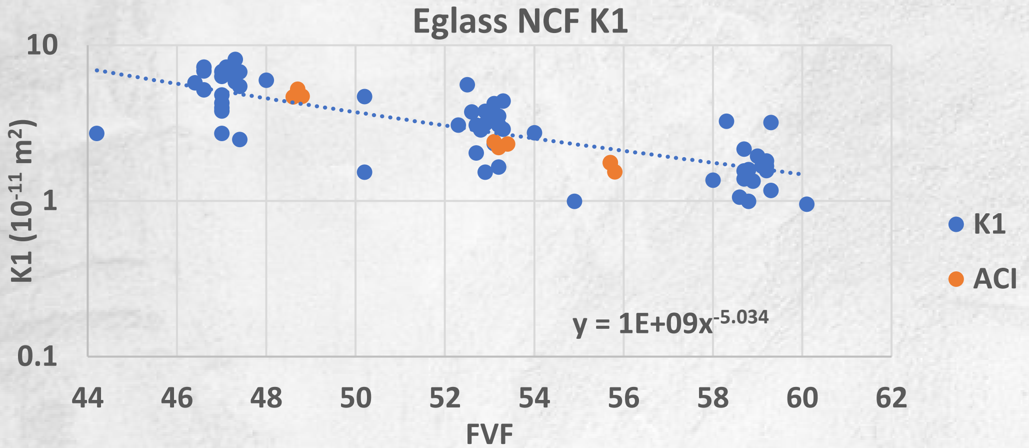
- Should conform to ISO draft: *Experimental Characterization of In-Plane Permeability of Fibrous Reinforcements for Liquid Composite Moulding*
  - Test fluid injected above atmospheric pressure (Maximum 0.3MPa)
  - Specimen thickness control
    - Test apparatus stiffness (maximum 2% cavity height deflection under pressure)
    - Repeatable spacing between two halves of test apparatus
    - Measurement procedures to verify cavity uniformity
  - Fluid pressure transducer (0.5% FS accuracy, FS < 2MPa)
  - Specimen edge length 30 times the injection port radius

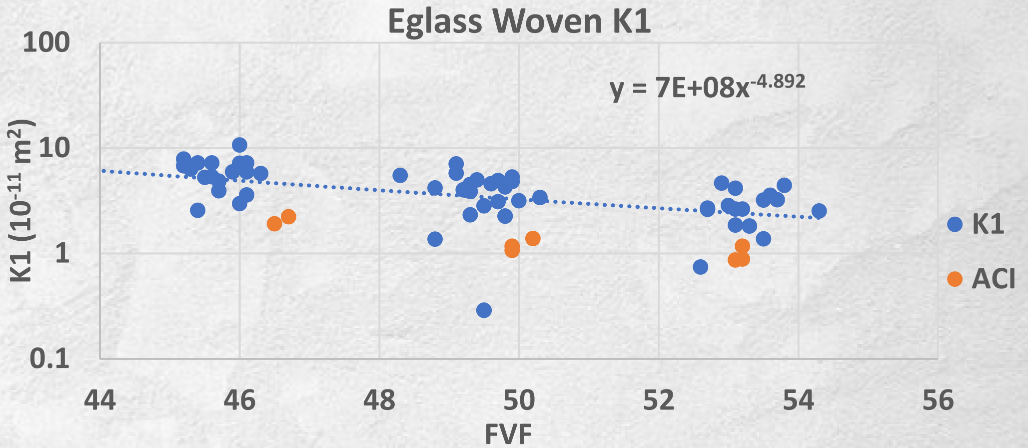
Permeability rig V2

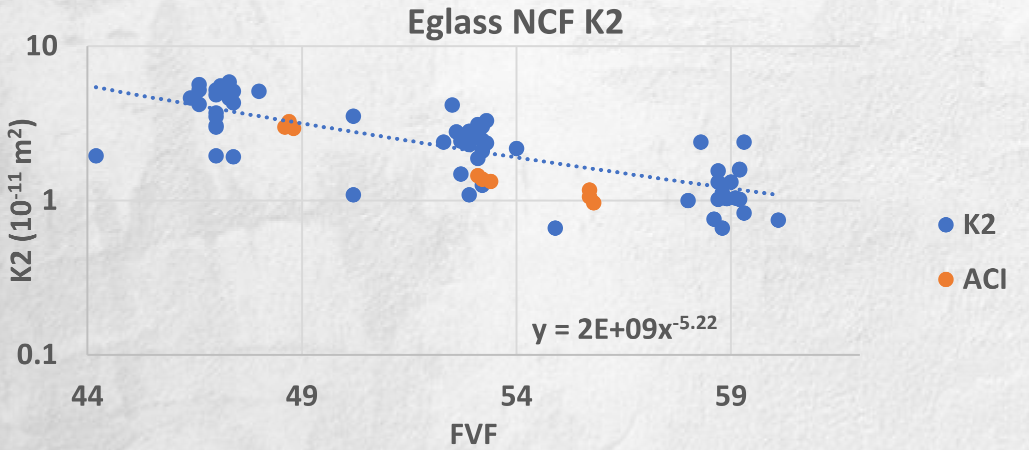


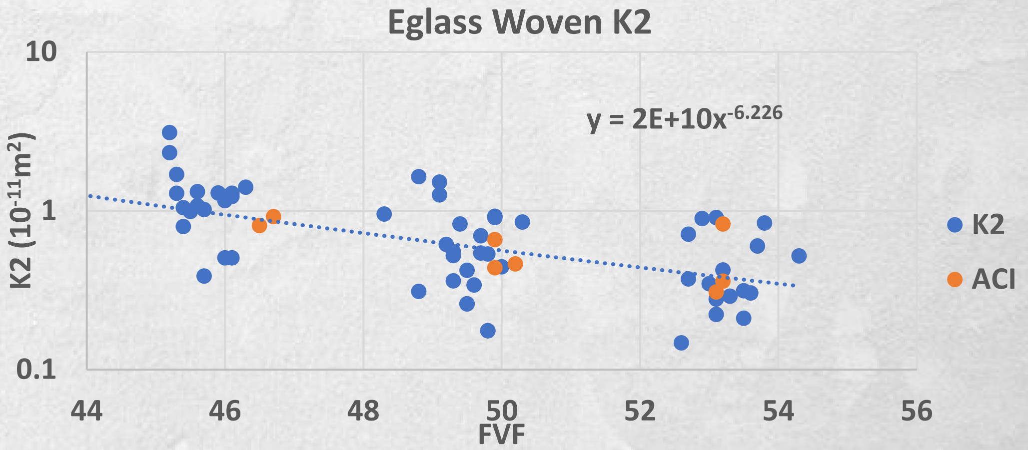


How do we compare to benchmark?







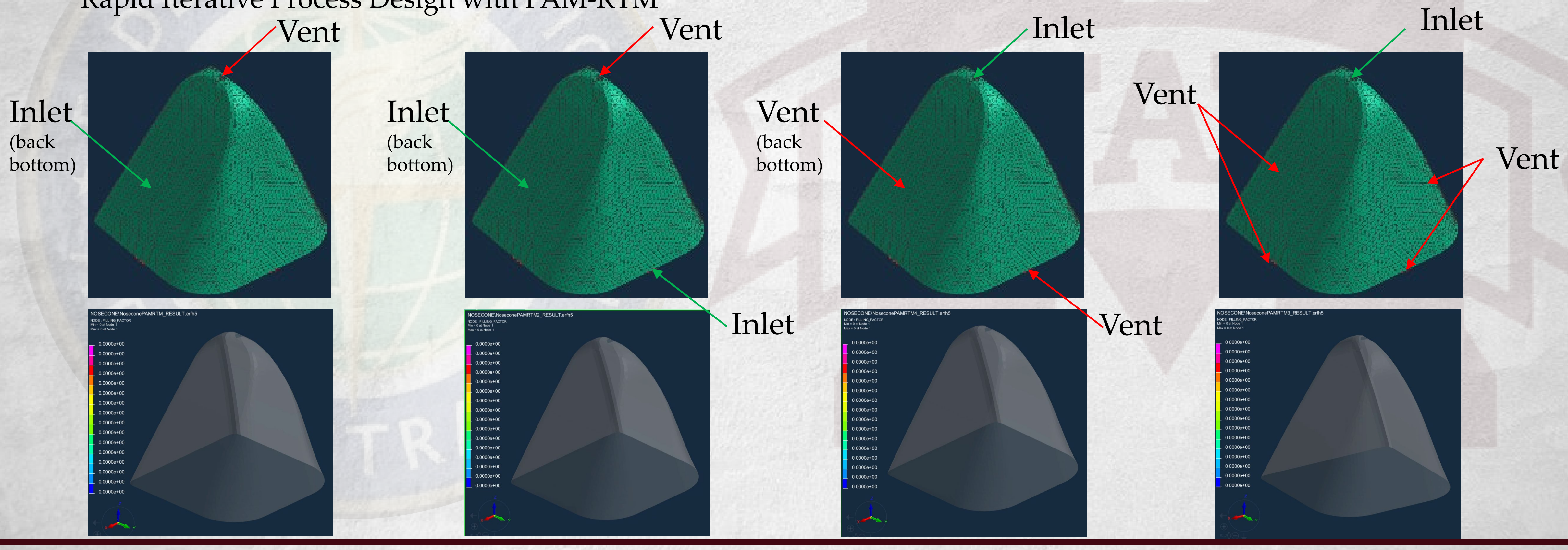


Technology Readiness for Stitched Resin Infusion

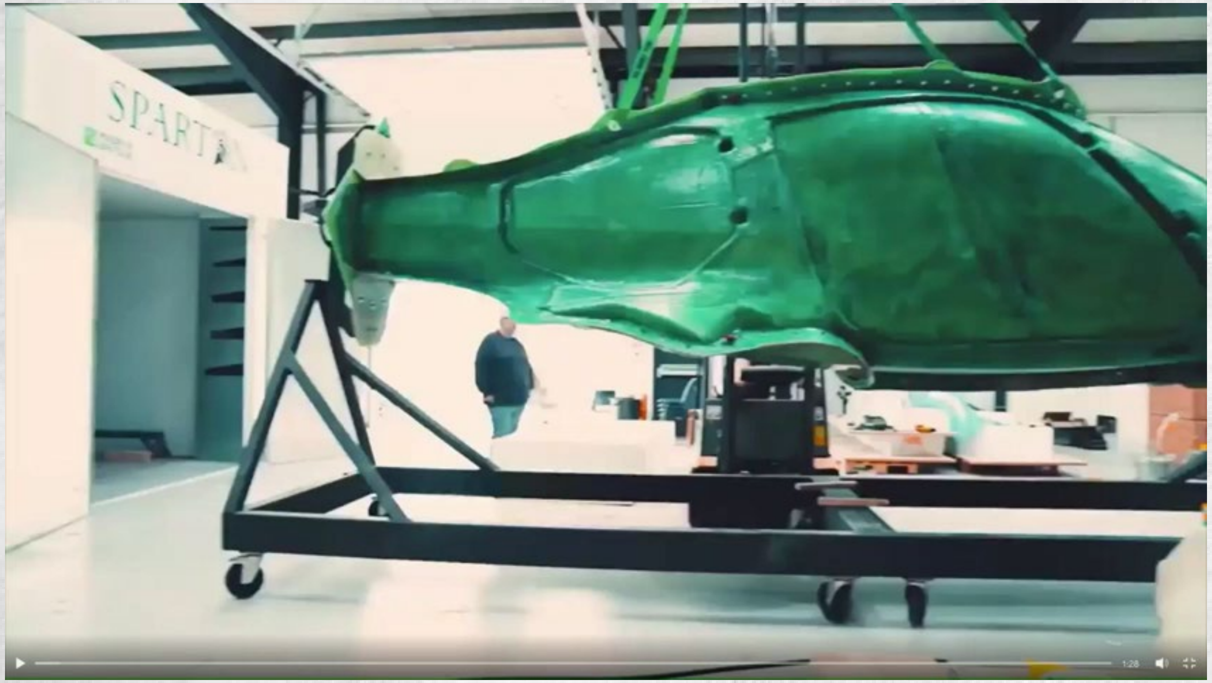
Phase II: Microcracking, NCAMP equiv., simulation, & preliminary testing for demonstrator

Simulation and Permeability

Rapid Iterative Process Design with PAM-RTM



Hill Helicopters



https://www.linkedin.com/feed/update/urn:li:activity:7043914894076772352/

https://www.hillhelicopters.com/

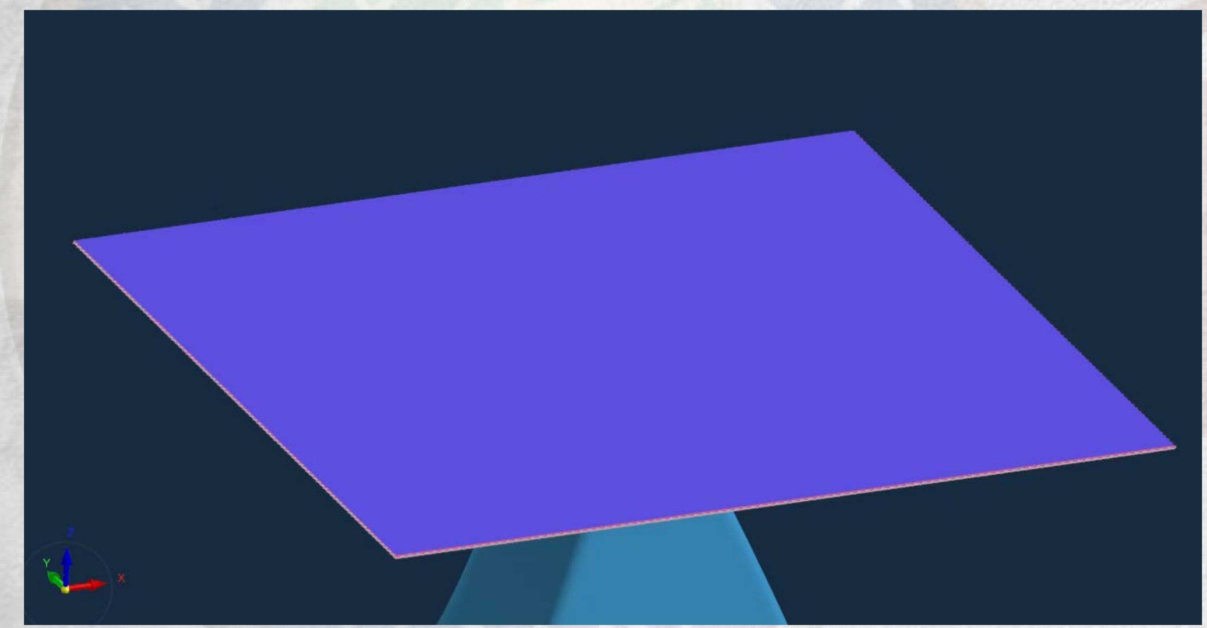
Questions

Technology Readiness for Stitched Resin Infusion

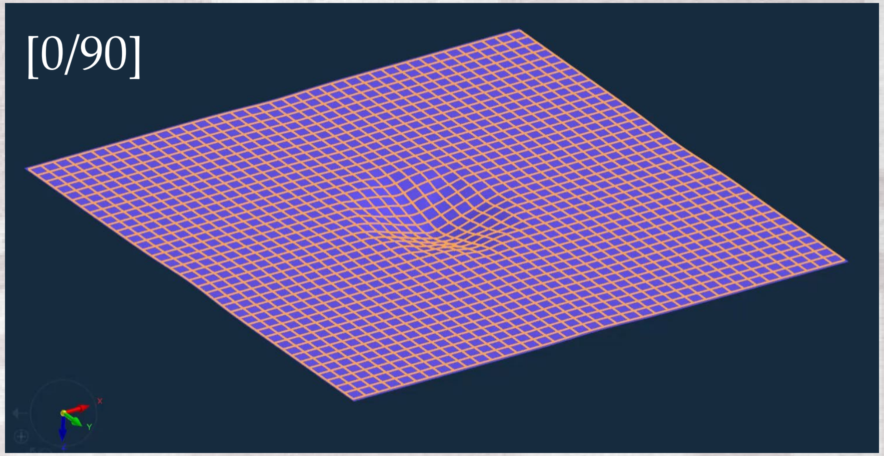
Phase II: Microcacking, NCAMP equiv., simulation, & preliminary testing for demonstrator

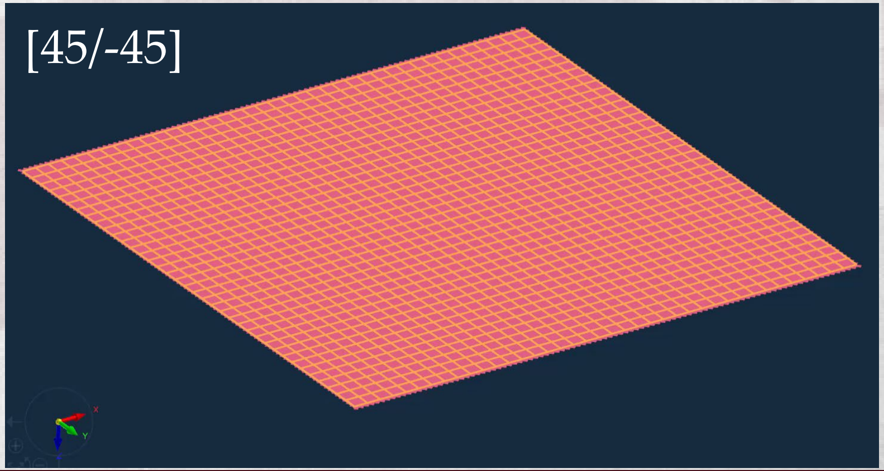
Simulation and Permeability

Multi-Layer Draping Simulation with PAM-FORM



Simulation is more complex for a single-sided hard tool



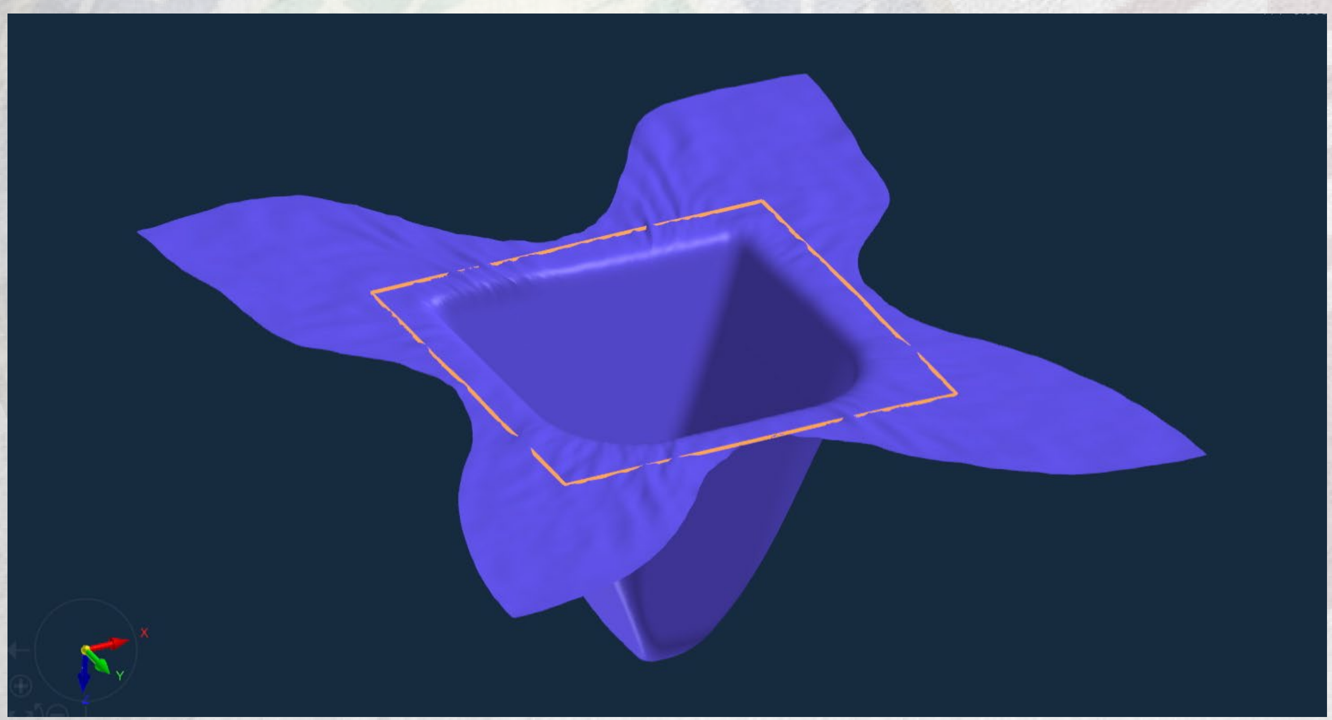


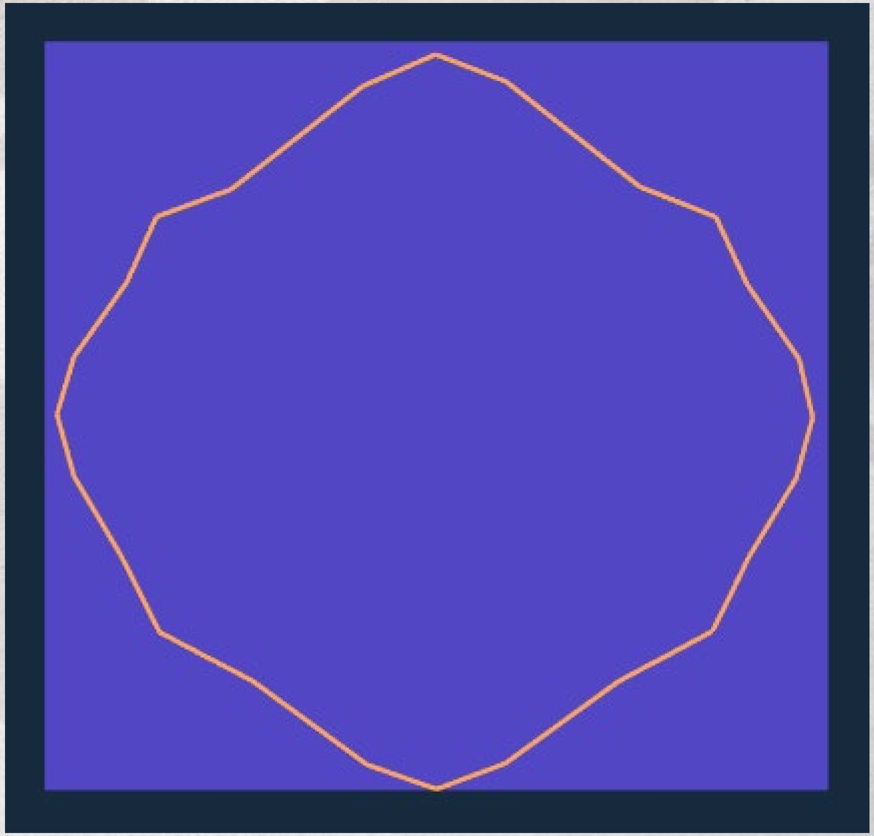
Technology Readiness for Stitched Resin Infusion

Phase II: Microcacking, NCAMP equiv., simulation, & preliminary testing for demonstrator

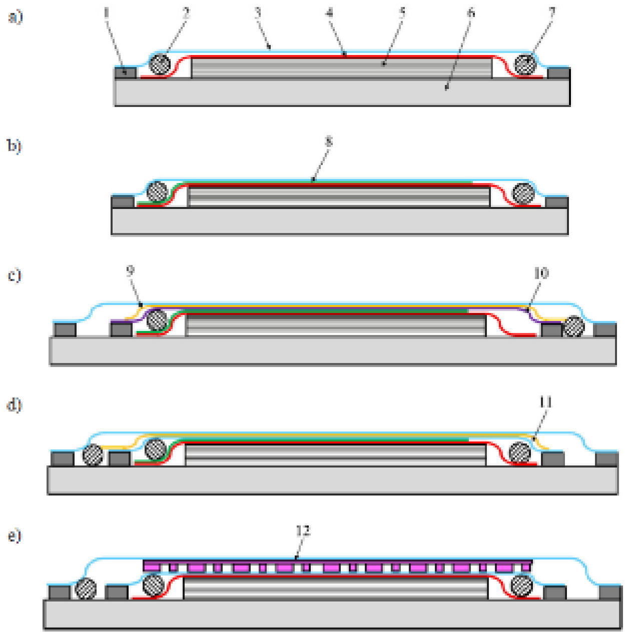
Simulation and Permeability

Efficient Ply Design for Reduced Waste





Questions?



1: Sealant tape 2: Resin Inlet 3: Vacuum Bag 4: Release Fabric
5: Fibre Stack 6: Mould 7: Vacuum Outlet 8: Distribution media
9: Breather 10: Membrane 11: Inner Vacuum Bag 12: Pressure Distributor

Fig. 1. Schematic description of the process variants; (a) VARTM, (b) SCRIMP and CAPRI, (c) VAP, (d) DBVI, and (e) PI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)